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Final state interactions in 3-body decay: challenges and future

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Three-body hadronic decays of B and D mesons are a superb laboratory for studying Charge-Parity (CP) violation and hadronic Final states Interactions. The gigantic samples of B and D decays collected by the LHCb (and more to come from others) experiments motivated theoretical efforts in the past decade towards building models that are based on more solid grounds. I presented an overview of these models. In particular, interesting results one obtain for $B^+ \to \pi^-\pi^+\pi^+$ with novel mechanisms of the CP asymmetries pattern observed in the Dalitz plot.

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1. Introduction

The precise study of hadron decays is one of the most powerful tools in the arsenal of particle physics, as it allows us to explore energy/mass scales not accessible by other means. The vast number of hadron decays amassed by the Large Hadron Collider beauty (LHCb) experiment at CERN has led to a revolution in experimental precision in this field. Many of the most exciting results involve multibody hadron decays; with some measurements finding tension with SM predictions to the matter-antimatter asymmetry, such as the unexpectedly large CP violation observed in $B \to hhh$ transitions ($h = \pi, K$) [1] and the first observation of charm CP violation in two body decays [2] $\Delta A_{dirCP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = (-1.54 \pm 0.29)10^{-3}$.

The current situation in three-body hadronic decay is progressing on the experimental side. More comprehensive investigations can be done nowadays, using the very large and pure samples provided by the LHC experiments, and still more data is expected in the near future, including neutral particles, with Belle II, BES III and LHCb (Run 2) experiments. These decays involve two distinct sets of interactions. They begin with a primary vertex, in which the light $SU(3)$ quarks produced in the weak reaction disturb the surrounding QCD vacuum and give rise to an initial set of mesons. This state then evolves by means of purely hadronic final state interactions (FSIs), whereby mesons rescatter many times before being detected. There are, however, many challenges on the theoretical side to fully describe the dynamics of those decay, in particular, the role of hadronic final state interactions and their rich structure.

In this work, I present the different contributions that FSI can provide to the understanding of B and D multi-body decays. I discuss some challenges and ways to over take them in a near future. In section 2 we first define what we called as final state interactions (FSI) and present a theoretical sound model to describe two-body FSI. In section 3, we show how FSI is crucial to understand CP violation in B decays and present some novel mechanism we developed to high mass. In section 4, I close with our final remarks.

2. Final state interaction in three-body decays

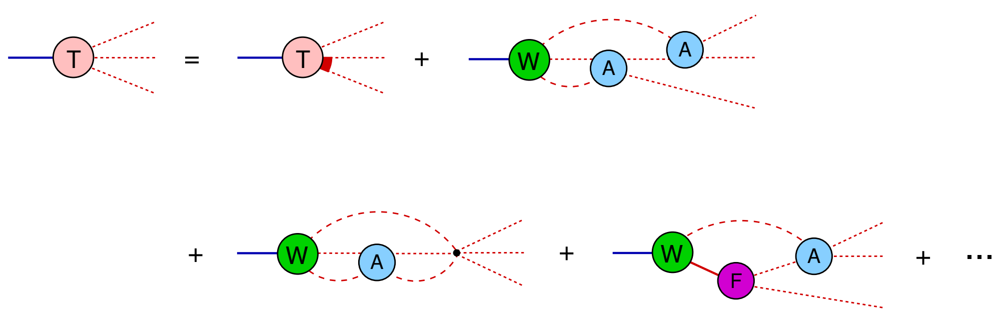

Figure 1: A pictorial representation of Three-body decay followed by final State interaction, representing all kind of interactions once the mesons are produced from a weak decay.

Final State Interactions (FSI) are the key towards understanding the hadronic effects in multi-body decays, where the above-mentioned tensions with the SM lie. Generally, any three-body

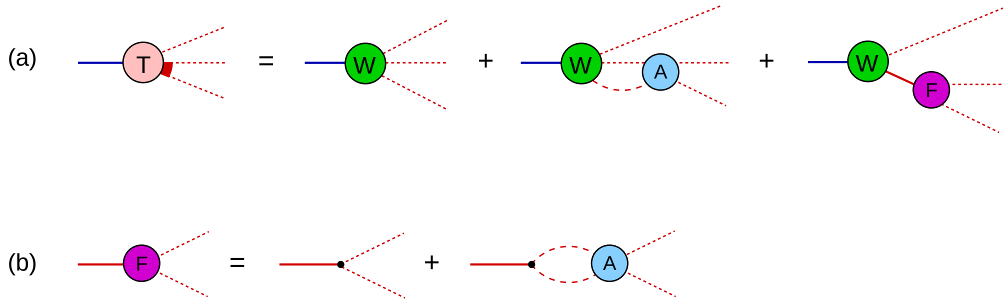

Figure 2: The standard $2+1$ approximation A pictorial representation of Three-body decay followed by final State interaction, representing all kind of interactions once the mesons are produced from a weak decay.

heavy meson decay can be represented by the series of diagrams given in Fig. 1, where W represents the weak vertex topologies, A is the two-body interaction amplitude, F the resonance form-factor production, given by Fig.2(b), and the first diagram represents the (2+1) approximation where the interaction with the third particle is neglected, as given by diagrams in Fig2(a). As illustrated in Figs. 1 and 2, the mesons produced in a weak decay can go directly to the detector and give rise to a *non-resonant* contribution. Alternatively, it is possible that the hadrons produced have various forms of strong interactions before reaching the detector. In this case, one talks about *final state interactions*, which are necessarily strong.

Independently of the weak interaction topologies and the approximation used to describe the three-body dynamics, the meson-meson interaction amplitude A is a main building block. The knowledge of this amplitude up to high energy is needed to describe the decay amplitude, which is a challenge to the phenomenology community.

The main model used to analyse data and characterize resonances are the standard isobar model. Its basic assumption is that a decay amplitude can be represented by a coherent sum of both non-resonant and two-body resonant contributions, with the latter described by a Briet-Wigner function depending on resonance mass m_k and a width Γ_k, given by

$$[\text{line shape}]_k \;\to\; [\text{BW}]_k = \frac{1}{[s-m_k^2+i\,m_k\,\Gamma_k]}. \tag{2.1}$$

There are, however, some limitations in this approach that results in serious flaws of the data analysis models already rather clear, such as: it violates two-body unitarity when there is more than one resonance with the same quantum numbers, it does not incorporate isospin and, especially important, it is totally unsuited for dealing with coupled channels. In the $SU(3)$ sector, scattering amplitudes for pions, kaons and etas are strongly coupled and cannot be represented as sums of individual contributions. At present, as one knows, QCD cannot be directly applied to heavy meson decays, but their effective counterparts can. Effective lagrangians rely just on hadron masses and coupling constants, ensuring that the physical meaning of parameters is preserved from process to process. This differs from the standard isobar model where the physical meaning of parameters it yields from data fits can be distorted due to the above mentioned conceptual gaps.

In a recent work [3] we explore the two-body scattering amplitudes, departing from effective lagrangians [4, 5] aiming at constructing guess functions for heavy-meson decays. The meson-

meson interaction amplitudes are directly associated with observed quantities and also important substructures of hadronic decay amplitudes.

In a previous model, developed for $D \to KKK$ [6] we developed the first seed of the present model where the meson-meson amplitudes where derived in the K-Matrix approximation and resulted in a good fit to LHCb data[7]. A considered extension of these ideas result in an SU(3) meson-meson tool kit [3], where we explore the main characteristic of a two-body interaction in a coupled-channel and multi-resonance description to be used in amplitude analyses of hadron decays.

2.1 Meson-Meson interaction

To be concise, I present just a summary of the four key ingredients to our amplitude [3]:
a. coupled channels - this sector of the problem is rather standard and model independent. In our notation, the coupling among the various channels is implemented by the mixing matrices $M_{ab}^{(J,I)}$.
b. multi-resonance dynamics - We add as many resonances per channel needed. While in kernels, resonances have no widths and are characterized just by their naked poles. The width will rise from the unitarization procedure. The inclusion of several resonances is performed by adding these poles in the unitarization scheme.
c. unitarization - We neglect four-meson intermediate states and the unitarization of amplitudes is directly associated with the s-channel two-meson propagators Ω that occur in the full scattering amplitude. These functions contain real and imaginary parts: $\Omega = \Omega^R + i\,\Omega^I$. The latter are free from ambiguities and constitute the only source of imaginary terms in the amplitudes $A_{(k\ell|ab)}^{(J,I)}$. In particular, resonance widths are necessarily proportional to Ω^I. The real component, Ω^R, has infinite components which are replaced by renormalization constants.
d. free parameters - The parameters entering our amplitudes consist basically of masses and coupling constants and, in principle, are completely free. Thus, our amplitudes are guess functions with open parameters, to be determined by fits do data. Most of the symbols used to label these parameters were borrowed from chiral perturbation theory, especially Ref.[5]. Their numerical meanings, however, are not exactly the same. In chiral perturbation theory, the values of parameters are extracted by comparing results from calculations performed to a given order with observables. As loops are divergent and need to be renormalized, values for parameters quoted in the literature also depend on renormalization scales. This kind of procedure is theoretically consistent and yields a precise description of low-energy phenomena.

Those amplitudes are ready to be implemented in real data and are under study in on going LHCb amplitude analysis.

3. FSI to understand CP violation

The relevance of FSI to the understanding of CP violation (CPV) pattern was proved recently by the experimental results from charmless three-body B decays. LHCb had shown a rich distribution of CPV within the Dalitz phase-space, the so called Mirandizing distribution[1] [1, 9, 10].

[1]CP asymmetry distribution in a Dalitz plot [8],

Positive and negative CP asymmetry are frequently seen in the same B decay channel and sometimes very close to each other in the phase-space, as have been observed in $B^{\pm} \to K^{\pm}\pi^{-}\pi^{+}$ and $B^{\pm} \to \pi^{-}\pi^{+}\pi^{\pm}$ decays at low $\pi\pi$ mass. These particular phenomena can be explained through the interference term between the σ and the $\rho(770)$ resonances [1, 11]. Another important source of CP asymmetry comes from the $\pi\pi \leftrightarrow KK$ rescattering, which couples different decay channels, namely, $B^{\pm} \to K^{\pm}\pi^{-}\pi^{+}$ with $B^{\pm} \to K^{-}K^{+}K^{\pm}$ and also $B^{\pm} \to K^{-}K^{+}\pi^{\pm}$ with $B^{\pm} \to \pi^{-}\pi^{+}\pi^{\pm}$ [1, 9, 10, 11, 12]. Between others, these two sources of CP violation were already confirmed for $B^{\pm} \to \pi^{-}\pi^{+}\pi^{\pm}$ [13, 14] and $B^{\pm} \to K^{-}K^{+}\pi^{\pm}$ decay channels [15] through a recent amplitude analysis performed by the LHCb collaboration for the Run I data. There are also strong experimental evidences for CPV in the Dalitz phase-space along the high mass region in all of those charged charmless B three-body decays [1]. Although the source for this CPV is not yet identified, we can assume that the variation of the CP asymmetry in the Dalitz plane is originated by a running strong phase along the phase-space, since the dominant weak phase contributing to these decays is the CKM phase γ, which must be a constant.

In a recent work [16] we connect those ideas and proposed a theoretical framework to understand the observable global charge- parity (CP) violation in charmless three-body $B^{\pm}$ decays. Our decay amplitudes consider the effects of the $\pi\pi \to KK$ rescattering treated within a CPT invariant framework together with the U-spin symmetry relation, $s \leftrightarrow d$, which results $\pi \leftrightarrow K$ in the final state. This approach applied to a two-channel model provides the magnitudes and the correct signs of the ratios of the global CP asymmetries for $B^{\pm} \to K^{\pm}\pi^{-}\pi^{+}$, $B^{\pm} \to K^{-}K^{+}K^{\pm}$, $B^{\pm} \to K^{-}K^{+}\pi^{\pm}$, and $B^{\pm} \to \pi^{-}\pi^{+}\pi^{\pm}$ decays, qualitatively consistent with those obtained from the available experimental data. In addition, by considering the neutral channels, we predict the ratios for the global CP asymmetries for these decays.

Although data is still not as precise as we would desire, there will be new high statistics soon which will allow us to better address this issue. From the theoretical side, in the proposed CPT constrained framework including FSI, we only take into account the S-matrix in the charged coupled channels $\pi\pi$ and KK in the S-wave. But besides the interactions among the charged mesons, one can have the coupling to the neutral ones along with other isospin zero meson pairs such as $\eta\eta$ as discussed in detail in [3].

3.1 localized CPV at high mass

Moving from the Global to de localized CP violation, in Ref. [17, 18], we proposed a new source of strong phase variation, associated with the possible $D\bar{D} \to K^{+}K^{-}$ rescattering, which couples the $B^{\pm} \to D\bar{D}K^{\pm}$ to $B^{\pm} \to K^{-}K^{+}K^{\pm}$ and the $B_c^{\pm} \to D\bar{D}\pi^{\pm}$ to $B_c^{+} \to K^{-}K^{+}\pi^{+}$ decay channels. In the later we have also considered the contribution of the channel $B_c^{\pm} \to D\bar{D}_sK^{\pm}$ through $D\bar{D}_s \to K\pi$ rescattering. In these studies, we concluded that the long distance hadronic loop originated by the double charm penguin contribution can produce a strong phase that changes along the Dalitz phase-space. This phase variation can change the sign of the CP asymmetry, as observed in experimental data [1][2], if the associated amplitude is interfering with another one carrying the weak phase.

[2] see LHCb-PAPER-2014-044 supplemental material at https://cds.cern.ch/record/1751517/files/.

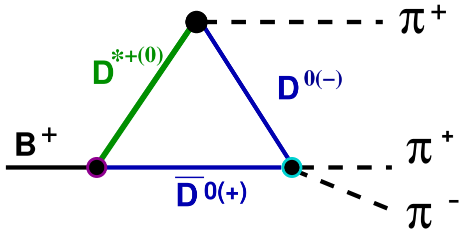

Figure 3: Charm loop contribution to $B^{\pm} \to \pi^-\pi^+\pi^{\pm}$ decay, where vertex $D\bar{D} \to \pi\pi$ is described by a phenomenological amplitude with the χ_0^c as a bound state bellow threshold.

To investigate the charm FSI in $B^{\pm} \to \pi^-\pi^+\pi^{\pm}$, in a recently study [19] we modify our previous phenomenological amplitude for $D\bar{D} \to KK$ [18] and generalize it for $D\bar{D} \to \pi\pi$, as shown in Fig. 3. Furthermore, χ_c^0 is introduced as resonant state below the $D\bar{D}$ threshold. This is an improvement with respect to the previous approach and different from considering only the contribution of χ_c^0 to the $D\bar{D} \to \pi\pi$ transition as a Breit-Wigner resonance.

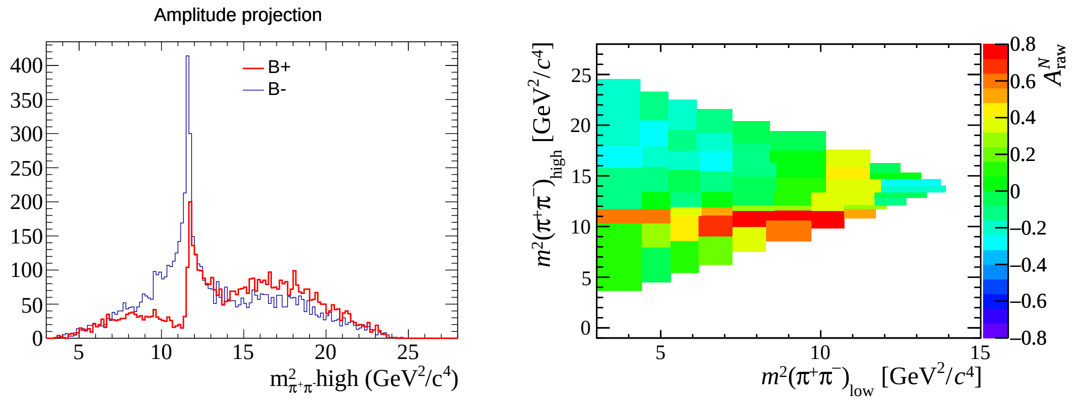

Figure 4: Left: LAURA++ output for the integrated decay rate for model II with the NR amplitude having a strong phase of 45^o and weak phase of 70^o [?] with twice the magnitude the charm loop one. Right: Miranda technique [8] applied to expose the CP violation in different regions of the $B^{\pm} \to \pi^-\pi^+\pi^{\pm}$ phase-space for model II.

The final model for the $B^{\pm} \to \pi^-\pi^+\pi^{\pm}$ decay amplitude for the high mass region we were interested, includes a contribution from a tree $b \to u$ nonresonant amplitude interfering with the hadronic charm loop with a s-wave $D\bar{D} \to \pi\pi$ rescattering described above. The resulting amplitudes and CP asymmetry are shown in Fig.4, where as we can see, the CP asymmetry distribution mimic qualitatively the one reported by LHCb Run I data in the high mass region [1]. This gives a possible interpretation of the mechanism behind these challenging experimental results.

4. Final Remarks

We discuss above different examples of the relevance of final state interactions in B and D hadronic three-body decays. In B decays they are crucial to understand the CPV at low mass with

$\pi\pi \to KK$ rescattering and at high mass with charm rescattering triangles. Moreover, we also show that the $\pi\pi \to KK$ rescattering dominates the global CPV in $B \to hhh$.

In D decays, three-body effects are more relevant that in B decays. Because of the phase space, the nonperturbative effects are stronger. In our three-body model to $D^+ \to K^+K^-K^+$ we could extract information from $K\bar{K}$ scattering amplitude. In what concern CP violation in charm sector, after the recent observation from LHCb in $\Delta A_{dirCP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$, there is an intense search for CPV in three-body D decays. In particular, for $D^+ \to \pi\pi\pi$ and $D^+ \to KK\pi$ are described by the same weak vertex as $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ and the same mechanism of $\pi\pi \to KK$ we shown to important in B decays can be important for CPV searches in those charm decays.

As we discussed in this work, in all the three-body model used in amplitude analysis the two-body amplitude as coupled-channel description is crucial. In this direction, we provided the community with a tool kit for amplitude analysis with theoretically sound models to be applied in data.

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